Experimental Investigation of the Near-Wall Region in the NASA HiVHAc EDU2 Hall Thruster

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Abstract: The HiVHAc propulsion system is currently being developed to support Discovery-class NASA science missions. Presently, the thruster meets the required operational lifetime by utilizing a novel discharge channel replacement mechanism. As a risk reduction activity, an alternative approach is being investigated that modifies the existing magnetic circuit to shift the ion acceleration zone further downstream such that the magnetic components are not exposed to direct ion impingement during the thruster's lifetime while maintaining adequate thruster performance and stability. To measure the change in plasma properties between the original magnetic circuit configuration and the modified, "advanced" configuration, six Langmuir probes were flush-mounted within each channel wall near the thruster exit plane. Plasma potential and electron temperature were measured for both configurations across a wide range of discharge voltages and powers. Measurements indicate that the upstream edge of the acceleration zone shifted downstream by as much as 0.104 channel lengths, depending on operating condition. The upstream edge of the acceleration zone also appears to be more insensitive to operating condition in the advanced configuration, remaining between 0.136 and 0.178 channel lengths upstream of the thruster exit plane. Facility effects studies performed on the original configuration indicate that the plasma and acceleration zone recede further upstream into the channel with increasing facility pressure. These results will be used to inform further modifications to the magnetic circuit that will provide maximum protection of the magnetic components without significant changes to thruster performance and stability.

Nomenclature

GRC	=	Glenn Research Center
HiVHAc	=	High Voltage Hall Accelerator
I_e	=	collected electron current
T_e	=	electron temperature
V_p	=	plasma potential

I. Introduction

HALL thrusters are becoming an increasingly attractive option for NASA science missions. Under the support of the NASA Science Mission Directorate's In-Space Propulsion Technology Program, NASA is developing the High-Voltage Hall Accelerator (HiVHAc) propulsion system in support of Discovery-class NASA missions. In

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addition to mission performance benefits that can be realized with electric propulsion systems, significant cost savings can be achieved by using a Hall thruster system when compared to gridded ion and chemical propulsion systems.[1, 2]

Presently the HiVHAc thruster meets operational lifetime requirements through the use of a novel discharge channel replacement mechanism. As part of the HiVHAc thruster development, an alternative approach is now being investigated by NASA Glenn Research Center (GRC) and the Jet Propulsion Laboratory as a risk-reduction activity towards meeting the lifetime requirement for NASA science missions. This alternative approach is focused on modifying the existing magnetic circuit within the thruster in such a way as to shift the acceleration zone of the thruster downstream with negligible changes in performance and stability. If the acceleration of the plasma occurs far enough downstream such that erosion of the channel does not expose critical magnetic circuit components, then such a shift is deemed adequate to meet the operational lifetime requirements for the thruster for any given mission.

While various magnet and plasma simulation tools were used to determine if such modifications to the thruster magnetic circuit were feasible, experimental validation of the modifications was ultimately necessary. As part of the experimental validation, two magnetic field configurations were tested and compared – an original, baseline configuration and a new, “advanced” configuration that would advance the location of the acceleration zone further downstream. Preliminary testing with the two configurations indicated, based on the location of the erosion zone on the discharge channel, that the acceleration zone had been successfully moved downstream. However, specific plasma properties were needed along the channel walls in order to validate the plasma model that will need to be used as part of the redesign effort, as well as to correlate the plasma response to the changes made to the magnetic circuit and resulting field.

In order to measure these plasma properties, six flush-mounted Langmuir probes were placed within each channel wall in the vicinity of the thruster exit plane. The thruster was operated across a wide variety of discharge voltages and power levels with both the original and advanced magnetic field configurations, and the plasma potential and electron temperature were measured along the channel walls as a function of these conditions. Flush-mounted Langmuir probes have proven to be a useful diagnostic to measure erosion-relevant properties along the discharge channel walls of Hall thrusters.[3-12]

While the primary objective of this investigation was to determine how the plasma properties along the channel walls are altered between the original and advanced magnetic field configurations, a secondary objective was to determine how these properties change as a function of facility backpressure. There has recently been renewed interest within the community in the effects the vacuum facility has on thruster operation, stability, and performance. While some direct measurements of how the near-field and internal plasma properties change as a function of facility backpressure have been made using optical diagnostics,[13-15] most investigations on backpressure effects focus on thruster performance, far-field properties, and thruster oscillations/stability.[16-21] Therefore, measurements of erosion-relevant properties along the channel walls and how they are affected by facility backpressure would contribute towards the understanding of facility effects in general and the implications towards ground-testing of Hall thrusters during thruster development and flight qualification.

The paper is organized as follows: Section II describes the experimental apparatus for the investigation, including the vacuum facility, Hall thruster, and diagnostics used. Section III discusses the results of the plasma potential and electron temperature along the channel walls at various operating conditions and compares the profiles between the original and advanced configurations as well as at elevated facility pressures. Section IV provides a summary and overall conclusions from the investigation.

II. Experimental Apparatus

A. Vacuum Facility

This investigation was performed within Vacuum Facility 12 (VF-12) at NASA GRC. VF-12 is a cylindrical vacuum chamber that is 9 m in length and 3 m in diameter. It is equipped with eight cryopanels capable of providing a pumping speed of 170,000 L/s on xenon. Facility pressure was monitored by two hot-cathode ionization gauges mounted within the facility, one placed beneath the thruster (which is located near the chamber endcap opposite the cryopanels) and one placed mid-length along the vacuum chamber. Facility base pressures of 1×10^{-7} Torr were routinely achieved. For a total xenon flow rate of 7.6 mg/s, the measured facility pressure was 6.4×10^{-6} Torr, corrected for xenon. This also corresponded to the maximum facility pressure during the study (except for when the facility pressure was artificially increased during facility effects studies).

B. Hall Thruster and Support Equipment

The test article for this study is the NASA HiVHAc EDU2 Hall thruster. The HiVHAc EDU2 is a highly throttleable thruster which operates from 0.3 to 3.9 kW discharge power and 200 to 650 V discharge voltage, corresponding to 1200 to 2700 s of specific impulse. The EDU2 is a high-fidelity engineering model and has undergone extensive testing and characterization, including performance acceptance testing, vibration testing, plume divergence characterization, and integration testing with a power processor unit and xenon feed system.[19-25] The design also includes a novel channel replacement mechanism to achieve high operational lifetimes at high specific impulse operation. For this study, the thruster was mounted on an inverted pendulum thrust stand within VF-12, although thrust measurements were not taken due to the large number of probe wires routed from the thruster. Laboratory power supplies and mass flow controllers were used to operate the thruster throughout this investigation. Cathode flow rate remained fixed throughout the study at 0.45 mg/s. Magnetic field settings were kept at a fixed value for each configuration that maintained stable operation over the entire throttle table. This was done to minimize the number of variables in the investigation.

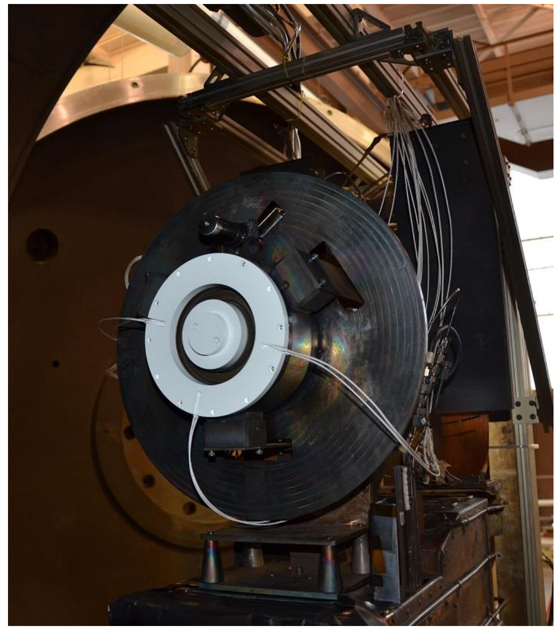

Figure 1. Photograph of the HiVHAc EDU2 thruster within VF-12 at NASA GRC with flush-mounted wall probes instrumented within each channel wall.

An auxiliary flow line was also installed within VF-12 along the mid-length of the chamber and pointed downstream of the thruster. This flow line was used to feed additional xenon into the facility to artificially increase the backpressure during thruster operation. The backpressure was increased at selected operating conditions and the plasma response was measured with the flush-mounted Langmuir probes. During this study, the thruster was operated at constant power by reducing the anode mass flow rate to maintain a constant discharge current.

C. Langmuir Probe

The Langmuir probe tips used in this study were composed of 0.41-mm-diameter pure tungsten wire whose ends were flattened with a diamond file prior to installation to ensure flushness with the channel walls. A new discharge channel was fabricated with modifications to facilitate the installation of the Langmuir probes. In particular, slots were machined at 3 discrete azimuthal locations within the outer channel wall to allow the tungsten wires to be routed radially outward with no bending required. The probes on the inner wall were bent 90 degrees and routed to the back of the thruster along the inside of the inner channel wall (see Fig. 2(a)). The tungsten wires themselves were approximately 25 mm in length and interfaced with high-temperature insulated lead wires. The wires were held in place using high-temperature ceramic paste within holes machined into the channel. This paste also served to insulate the exposed portions of the tungsten wire and pin-socket interface between the tungsten and lead wires. These lead wires were further protected by fiberglass sleeving until they reached an adequate distance from the thruster to avoid high heat loads, where they interfaced with shielded coaxial cabling for protection against electromagnetic noise. The cabling comprised the remainder of the electrical lines within the vacuum facility up to the vacuum feedthroughs.

Each channel wall was instrumented with six Langmuir probes that were placed at various axial distances from the thruster exit plane (see Fig. 2(b)). These probes were staggered azimuthally for easier installation, to allow for closer axial spacing and to minimize any probe-to-probe interactions. For this study, probe clusters of two were placed at approximately 3, 6, and 9 o'clock positions. The outer wall probes were slightly offset azimuthally from the inner wall probes to ensure no interactions along magnetic field lines.

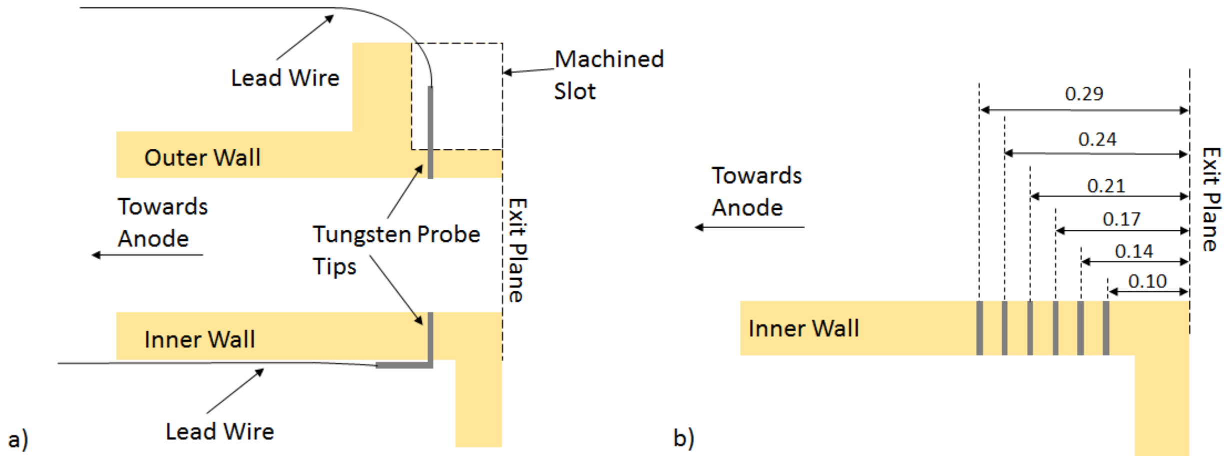

Figure 2. (a) Schematic illustrating how Langmuir probe tips were installed within each channel wall and how lead wires were routed to the back of the thruster. (b) Locations of each Langmuir probe (total of six) along the inner wall with respect to the thruster exit plane in units of channel lengths. Locations for the outer wall probes are similar to those shown for the inner wall, but not identical due to machining tolerances.

During operation, each probe was connected one at a time to a custom-made circuit box that would measure the applied voltage and collected current (see Fig. 3). Probe voltage was supplied by a commercially available 1000-V, 40-mA bipolar supply that was connected to a function generator. A symmetric triangle waveform at a frequency of 5 Hz was used to bias each probe during operation. A voltage divider comprised of 10-MΩ and 0.13-MΩ resistors were used to measure the voltage, while the collected current was measured across a 100-Ω, 25-W power resistor. These signals were passed through voltage-following instrumentation amplifiers to help reduce zero-shift and amplification noise before being passed through voltage-following isolation amplifiers that protect the data acquisition system (DACS). Blocking diodes were also placed across the inputs to the instrumentation amplifiers to protect them from large electrical spikes. Data were collected using the DACS for one second at an acquisition rate of 10 kHz. This resulted in ten I-V characteristics being collected per probe per operating condition, with each characteristic containing 1000 points.

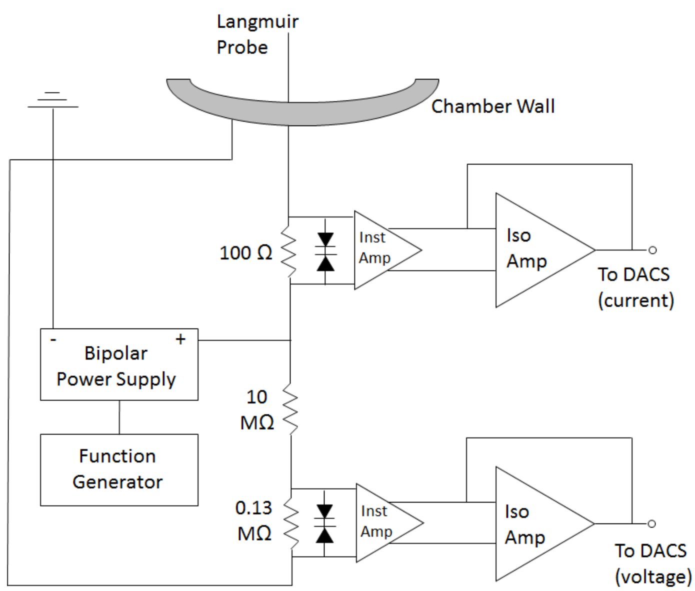

Figure 3. Electrical diagram of the circuit used to measure applied voltage and collected current from each Langmuir probe.

Data from all ten I-V characteristics were plotted together and boxcar averaged with a window of 25 points to smooth the data prior to analysis (see Fig. 4(a)). Analysis of the data largely followed simple Langmuir probe theory.[26, 27] First, the I-V characteristic was shifted by a value which yielded the most linear response in the transition region for determination of the electron temperature. This was performed to avoid dealing with sheath expansion effects in the ion saturation branch of the characteristic, as well as potential leakage currents that would artificially shift the trace in the positive current direction (excessive electron current). This technique was deemed acceptable because the primary focus of the study was determination of electron temperature and plasma potential, not ion density. Under most circumstances, the required shift corresponded to the collected probe current at approximately 2-3 electron temperatures below the probe floating potential. The electron temperature was determined by performing linear regression on the transition region while plotted in semi-log space, whose inverse slope corresponds to the electron temperature in eV. A similar regression was then performed on the electron

saturation region, and the probe voltage at which these two lines intersect was taken to be the plasma potential with respect to facility ground. These potentials were then shifted by the measured cathode-to-ground voltage, such that all reported plasma potentials are referenced with respect to cathode potential. Based on variations in the line fits for a given I-V characteristic, the uncertainties in electron temperature and plasma potential are conservatively estimated to be ±20% and ± 20 V, respectively.

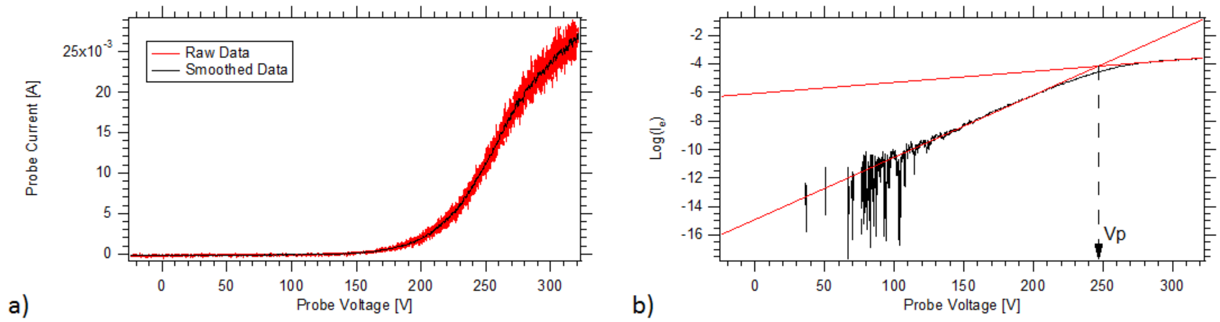

Figure 4. (a) Example Langmuir probe I-V characteristic, plotted both before and after boxcar averaging was performed. (b) Semi-log plot of corresponding electron current and determination of electron temperature and plasma potential.

III. Results and Discussion

Six flush-mounted Langmuir probes were placed within each discharge channel wall to determine the plasma properties near the thruster exit plane related to channel erosion. Data were collected at several operating conditions ranging from 300 – 650 V discharge voltage and 1.0 – 3.5 kW discharge power. Four representative operating conditions are presented below: 300 V, 1.0 kW; 300 V, 2.0 kW; 500 V, 2.0 kW; and 650 V, 3.5 kW. Data collected with the baseline magnetic field configuration will be labeled "original config," while data collected with the advanced magnetic field configuration will be labeled "advanced config." Results from varying the facility backpressure will also be presented for 300 V, 2.0 kW and 500 V, 2.0 kW.

A. Original vs. Advanced Magnetic Field Configurations

Figures 5 and 6 show the measured plasma potentials and electron temperatures along the inner and outer channel walls, respectively. All plasma potentials are reported with respect to cathode potential. Data could not be collected with the inner wall probe furthest downstream for the original configuration due to loss of electrical contact just prior to facility pumpdown. This probe was not deemed critical enough to warrant the time and risk of repair. Also, data could not be collected from certain upstream probes along the outer wall for the advanced configuration due to probe failures at elevated discharge voltages. It is evident from the plasma potential profiles that the acceleration zone begins further downstream in the advanced magnetic field configuration. In order to quantify this shift, the location of the upstream edge of the acceleration zone is determined. The upstream edge is defined here as the furthest downstream location at which the plasma potential is still within 10% of the discharge voltage. For instance, for a discharge voltage of 300 V, the location furthest downstream that still measures a plasma potential above 270 V is defined as the upstream location of the acceleration zone. Given the limited spatial resolution, the two probe positions that bound this location are provided as a range. Table 1 provides a comparison of the measured locations of the upstream edge of the acceleration zone for each operating condition and channel wall. The shift in acceleration zone is a function of both the operating condition and channel wall, and varies from as little as no change at all to as large as 0.104 channel lengths. The degree of shift between magnetic field configurations appears dependent upon the location of the acceleration zone in the original configuration, where larger changes occur if the original location is further upstream. It is also interesting to note that the upstream edge of the acceleration zone has less variation across operating conditions in the advanced magnetic field configuration, remaining between 0.136 and 0.178 channel lengths upstream of the exit plane.

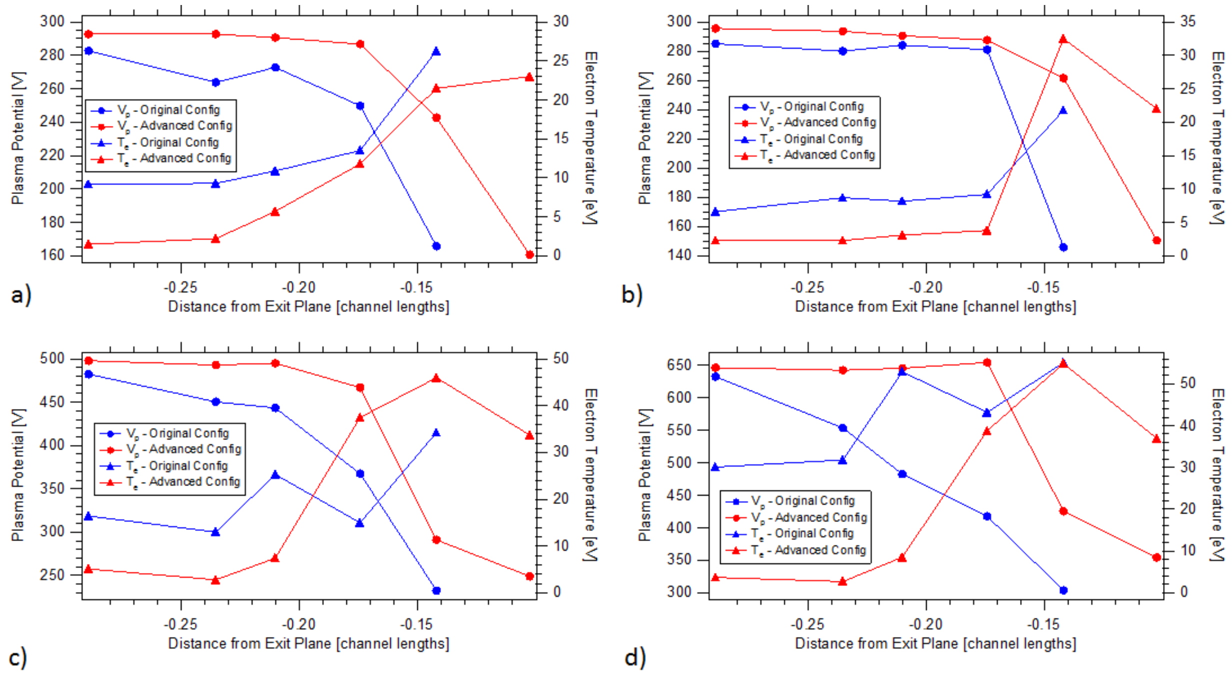

Figure 5. Comparison of measured plasma potentials (with respect to cathode potential) and electron temperatures along the inner channel wall between the original (baseline) and advanced magnetic field configurations for various operating conditions: (a) 300 V and 1 kW, (b) 300 V and 2 kW, (c) 500 V and 2 kW, and (d) 650 V and 3.5 kW.

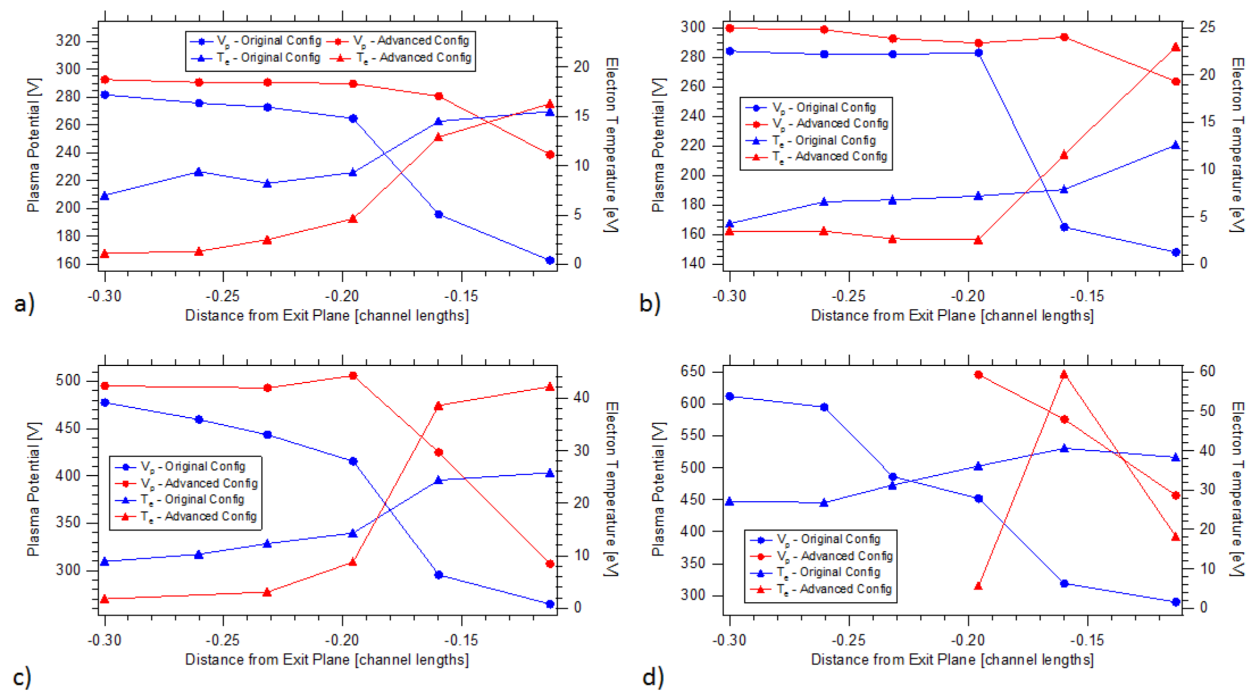

Figure 6. Comparison of measured plasma potentials (with respect to cathode potential) and electron temperatures along the outer channel wall between the original (baseline) and advanced magnetic field configurations for various operating conditions: (a) 300 V and 1 kW, (b) 300 V and 2 kW, (c) 500 V and 2 kW, and (d) 650 V and 3.5 kW.

Table 1. Comparison of the location of the upstream edge of the acceleration zone along the inner and outer channel walls between the original and advanced magnetic field configurations. All values are in units of channel lengths and referenced with respect to the thruster exit plane. The measured upstream edge of the observed erosion band is also provided for comparison.

	Inner Channel Wall		Outer Channel Wall	
	Original Config.	*Advanced Config.*	*Original Config.*	*Advanced Config.*
300 V, 1 kW	-0.192 ± 0.018	-0.158 ± 0.016	-0.214 ± 0.018	-0.136 ± 0.023
300 V, 2 kW	-0.158 ± 0.016	-0.158 ± 0.016	-0.178 ± 0.018	-0.136 ± 0.023
500 V, 2 kW	-0.223 ± 0.013	-0.158 ± 0.016	-0.246 ± 0.014	-0.178 ± 0.018
650 V, 3.5 kW	-0.262 ±0.027	-0.158 ± 0.016	-0.246 ± 0.014	-0.178 ± 0.018
Erosion Band	-0.307	-0.200 ± 0.002	-0.243 ± 0.008	-0.179 ± 0.007

The location of the "erosion band" on the channel walls themselves were measured after thruster operation. The erosion band is defined as the axial extent where erosion is evident on the channel wall, typically based on a lack of backsputtered deposition from the facility. Azimuthal asymmetry observed after operation with the original configuration (discussed further in Section III-B) resulted in slight variations in the location of the erosion band around the channel. To facilitate comparisons, the location that is reported corresponds to the azimuthal position at which the upstream edge of the acceleration zone at 650 V, 3.5 kW was measured. In instances where the upstream edge of the acceleration zone is bound by probes at different clocked positions, an average erosion band location with an uncertainty is reported. Table 1 includes the measured locations of the upstream edge of the erosion band for each channel wall and magnetic field configuration. The location of the upstream edge of this band was measured to be: -0.307 and -0.243 channel lengths for the inner and outer channel walls, respectively, in the original configuration; and -0.200 and -0.179 channel lengths for the inner and outer channel walls, respectively, in the advanced configuration. These values are in good agreement with the measured location of the upstream edge of the acceleration zone for 650 V, 3.5 kW, which corresponds to the location furthest upstream for all operating conditions. This is evidence that visual inspection of the channels after thruster operation can provide a good estimate of the upstream edge of the acceleration zone at 650 V, 3.5 kW.

Figures 5 and 6 also illustrate that the electron temperature rises more sharply in the advanced magnetic field configuration, while the original configuration exhibits a more gradual rise with higher electron temperatures further upstream. This trend is most evident at the higher discharge voltages. This difference is indicative of stronger potential gradients (i.e. electric fields) in the advanced configuration, although it is difficult to determine if this feature is present in the plasma potential profiles given the limited spatial resolution and extent. This trend is likely the result of the changes made to the shape of the magnetic field for the advanced magnetic field configuration, which affected not only the location but also the width of the acceleration zone along the channel walls.

B. Variations with Facility Backpressure

The facility backpressure was varied during testing of the original magnetic field configuration at various operating conditions. Additional xenon was flowed into the facility via an auxiliary line placed at mid-length of the vacuum chamber and pointed downstream of the thruster. While both ionization gauges indicated a similar rise in pressure, the gauge below the thruster was used to determine the magnitude of the increase. The discharge current was kept constant as the backpressure was varied by adjusting the anode mass flow rate. A pressure of "1X" corresponds to the nominal facility backpressure with no auxiliary flow, while a pressure of "2X" corresponds to twice the nominal facility backpressure, etc.

Figures 7 and 8 show the measured plasma potentials and electron temperatures along the channel walls at 300 V, 2 kW and 500 V, 2 kW, respectively. It is evident from the plasma potential profiles that the acceleration zone recedes further into the channel towards the anode with increasing facility backpressure. This trend is consistent with prior measurements performed on other thrusters at various backpressures using optical diagnostics.[13-15] This phenomenon was also observed during prior facility backpressure studies performed on HiVHAc within Vacuum Facility 5 at NASA GRC.[19, 21] It is interesting to note that the differences in profiles between 1X and 2X pressure at 300 V, 2 kW is larger than between 2X and 4X. This trend correlates with the required change in anode mass flow rate to maintain constant discharge current – a change of 2.7% in the flow rate was required between 1X and 2X pressure, but no change was required between 2X and 4X pressure. While this is indicative that the effect of facility backpressure on the plasma discharge is saturating, noticeable changes are still observed in the electron temperature profiles between 2X and 4X pressure despite having no effect on the discharge current.

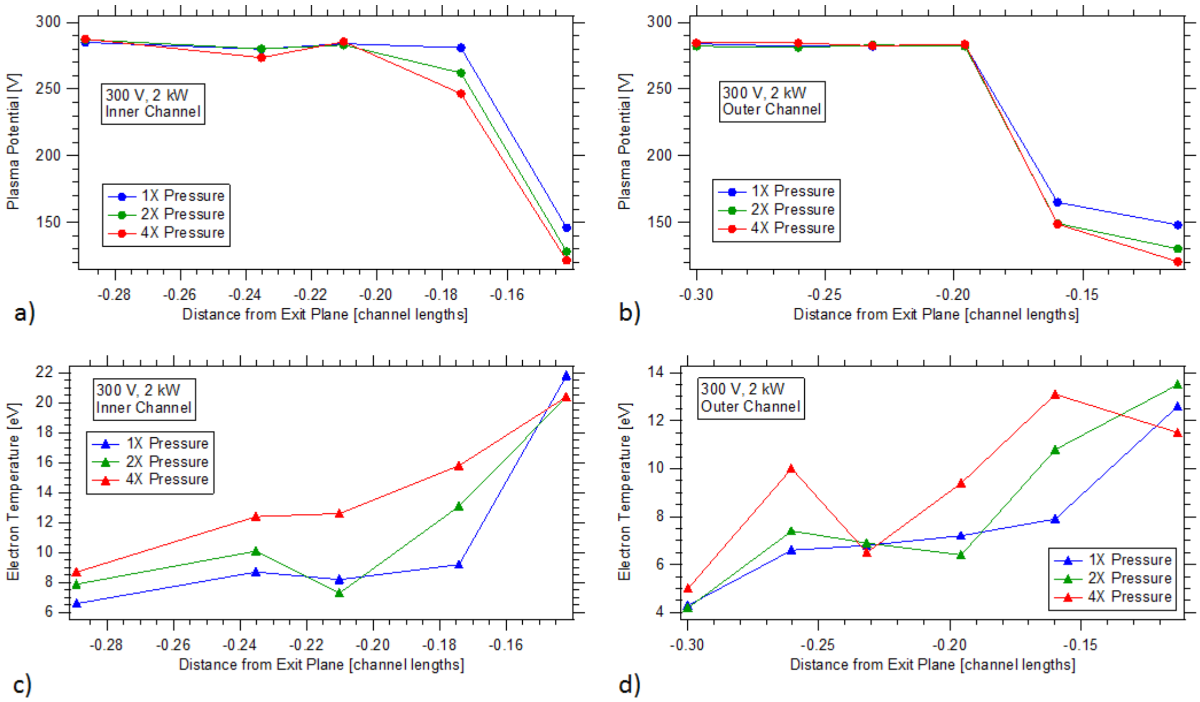

Figure 7. Comparison of measured plasma potentials (with respect to cathode potential) and electron temperatures along the channel walls at 300 V, 2 kW for various facility backpressures.

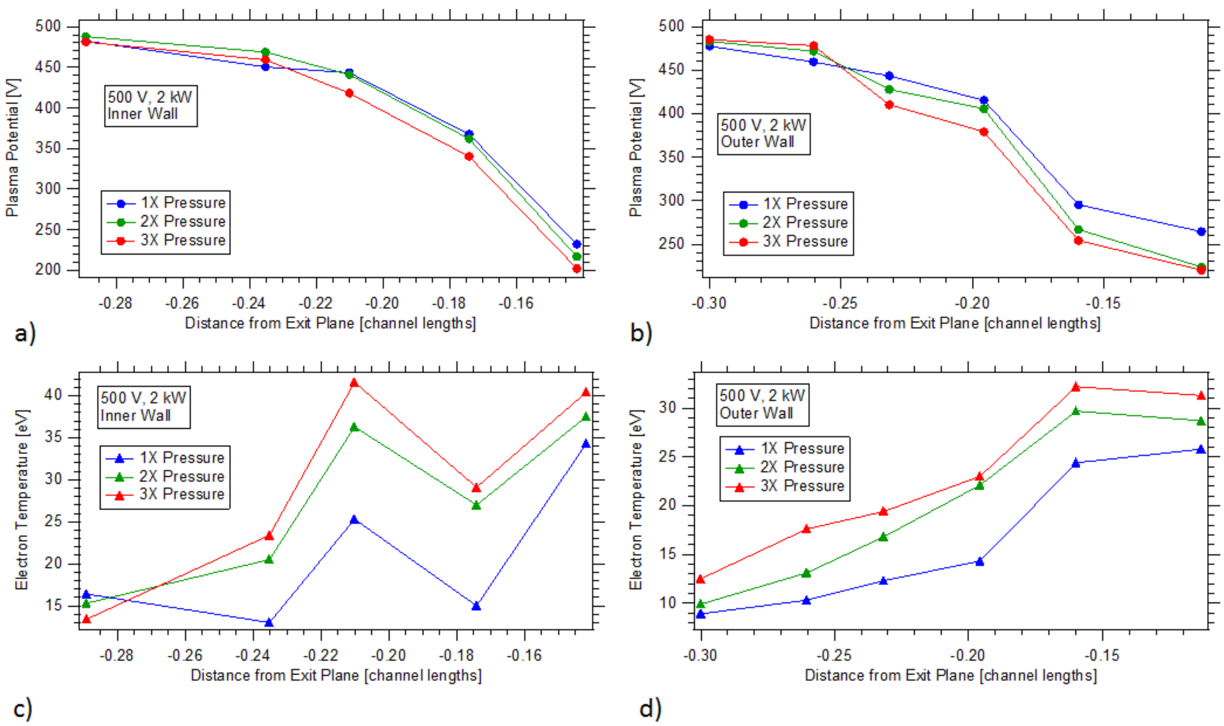

Figure 8. Comparison of measured plasma potentials (with respect to cathode potential) and electron temperatures along the channel walls at 500 V, 2 kW for various facility backpressures.

At 500 V, 2 kW, more evenly distributed changes are observed with increasing pressure. Each step increase in pressure required a change in anode mass flow rate of 1.2%. An increase in pressure to 4X the nominal value resulted in higher discharge current oscillations as well as sparks emanating from the discharge channel, possibly caused by the recession of the acceleration zone into a region of the channel that was originally coated in backsputtered material from the facility. Therefore, pressures above 3X the nominal value were not tested at 500 V, 2 kW. Recession of the acceleration zone into the discharge channel with increasing pressure indicates that channel erosion rates would increase at elevated facility pressures and therefore constitute a "worst case" scenario compared to erosion rates in flight. Recession of the plasma further into the discharge channel would also potentially result in increased plasma heat loading on the channel walls. However, additional factors would need to be considered such as changes to discharge oscillations, thruster performance, and erosion of other surfaces either on the thruster or the spacecraft.

Some of the axial profiles above appear to exhibit non-monatonic behavior which does not seem to be physical (e.g. electron temperature increasing, decreasing and increasing again). While this behavior could be due to measurement uncertainty, it may also be the result of azimuthally spreading out the probe locations. Inspection of the channel walls after thruster operation with the original magnetic field configuration revealed that the erosion band width on both walls was not azimuthally symmetric, but could vary by as much as 0.07 channel lengths. Therefore, it is possible the non-monatonic behavior is the result of interrogating different axial profiles that are spaced slightly apart. This effect would be greatest in regions where the gradients in properties are larger, resulting in higher sensitivity to changes in position. The cause of this asymmetry is presently unknown, but could be due to cathode placement at the 12 o'clock position or neutral flow non-uniformity caused by obstructed orifices or other issues with the propellant manifold. It is recommended that in future studies that utilize flush-mounted wall probes, all probes are kept within relatively close azimuthal proximity to each other in order to avoid potential issues of asymmetry. While this obfuscates interpretation of individual axial profiles, comparison of each profile across various pressures, or between the original and advanced magnetic field configurations, are still considered valid.

IV. Conclusions

As part of the development of the HiVHAc propulsion system, an alternative approach towards meeting the thruster lifetime requirement is being investigated as a risk reduction activity. Changes to the magnetic circuit were implemented in an effort to shift the acceleration zone downstream to prevent direct ion impingement on magnetic components over the operational lifetime of the thruster. Flush-mounted Langmuir probes were installed within the discharge channel walls to determine how the plasma properties changed between the original, baseline configuration and the modified, "advanced" configuration. Results from the probes indicate that the upstream edge of the acceleration zone shifted downstream by as much as 0.104 channel lengths, with higher voltage operation seeing larger changes in location. Electron temperature profiles also show a steeper rise in the advanced configuration, indicating stronger electric fields that may be the result of shape changes to the magnetic field. Facility effects studies performed on the original configuration indicate that the plasma and acceleration zone along the channel walls recede further into the discharge channel with increased facility pressure, which is consistent with previous studies on HiVHAc as well as other thrusters. This indicates that erosion and plasma heat loading of the channel walls may be higher in ground-testing than in flight. The results from this investigation will be used to inform future modifications to the magnetic circuit in the HiVHAc thruster to significantly increase lifetime while maintaining adequate performance and stability.

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